

# Supersymmetry 2014: $\mu$ -collider implications

Adam Martin  
University of Notre Dame  
([amarti41@nd.edu](mailto:amarti41@nd.edu))

MAP Spring Meeting, May 30th, 2014, Fermilab

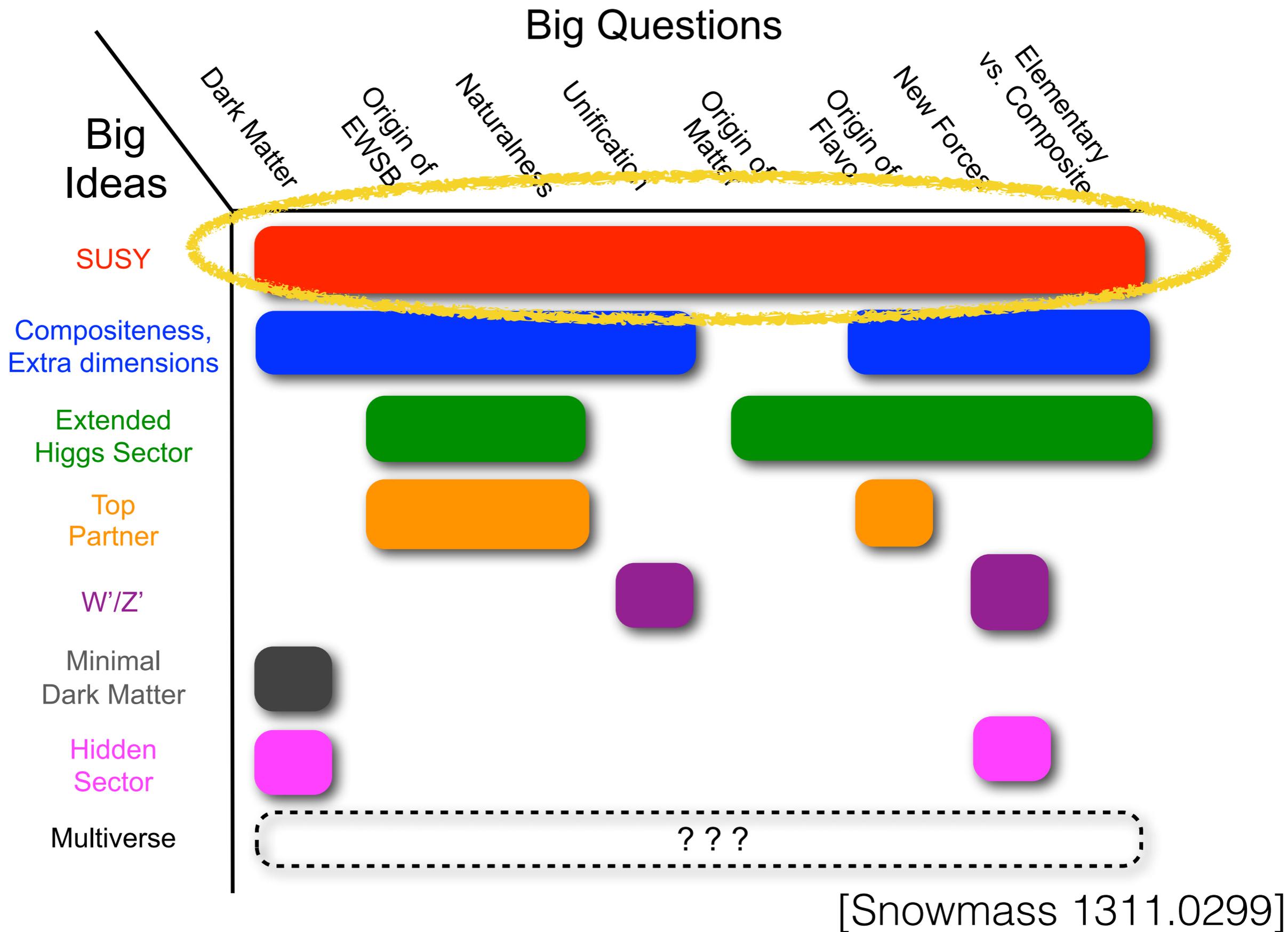
# Outline

SUSY as we knew it, pre-LHC

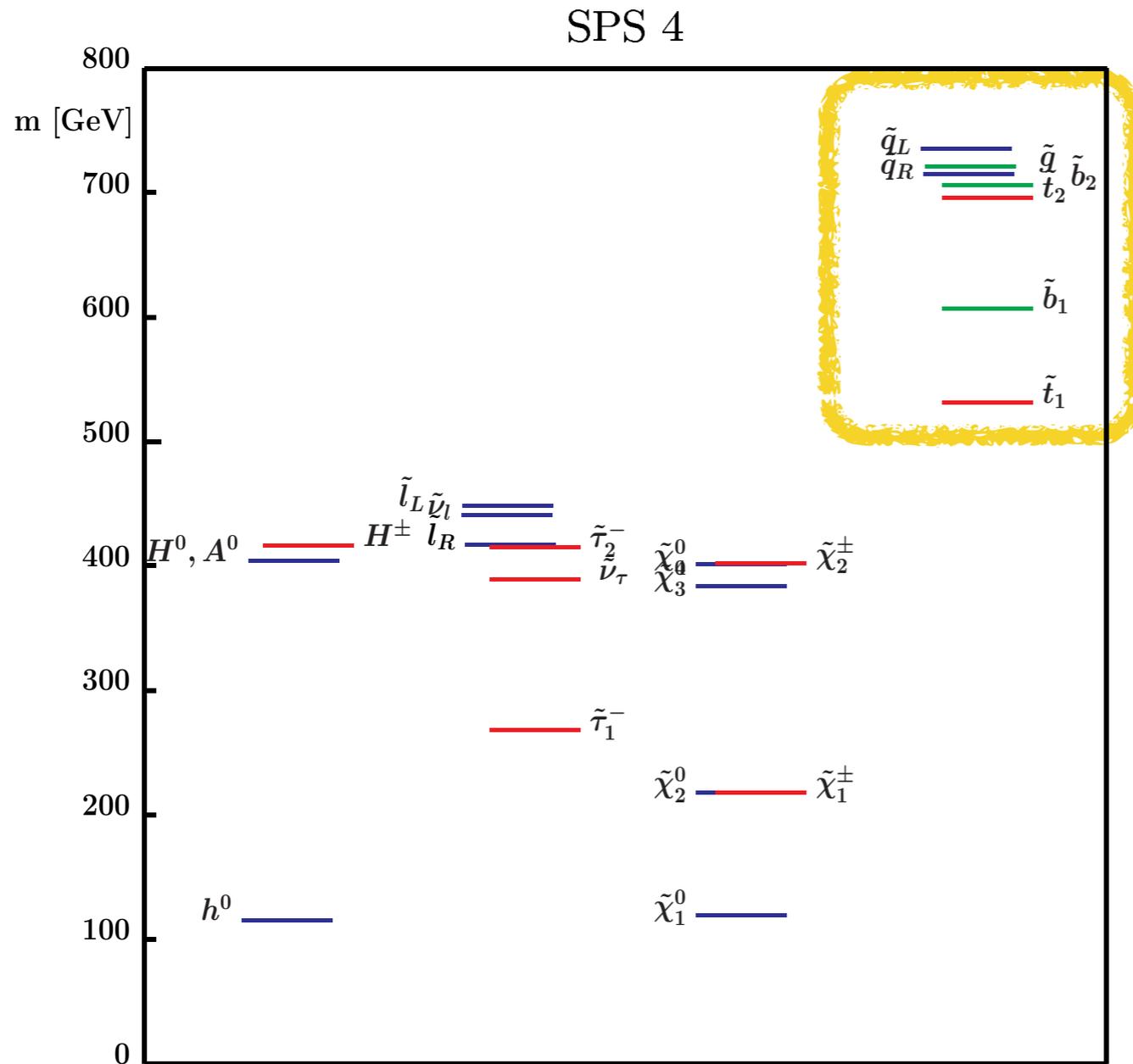
SUSY after 20 fb<sup>-1</sup>, 8 TeV + a ~126 GeV Higgs

where we go from here

# why supersymmetry?



# what was possible in SUSY, a la 2010



CMSSM-style spectra

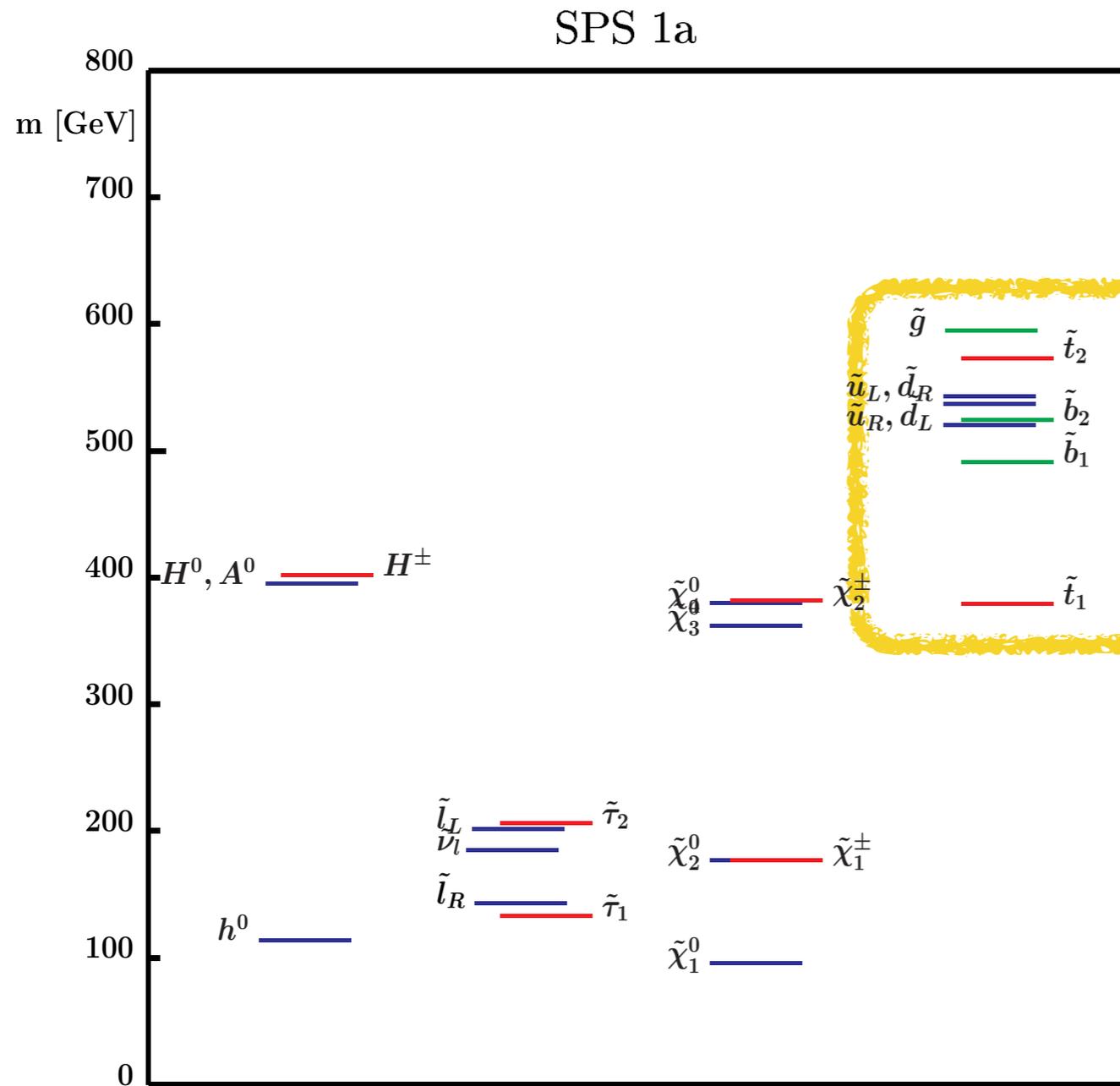
colored sparticles  $\approx 1000$  GeV,

similar mass for all squark generations & gluino

color neutral particles hovering right at the 100-200

[LesHouches 2011]

# what was possible in SUSY, a la 2010



CMSSM-style spectra

colored sparticles  $\approx 1000$  GeV,

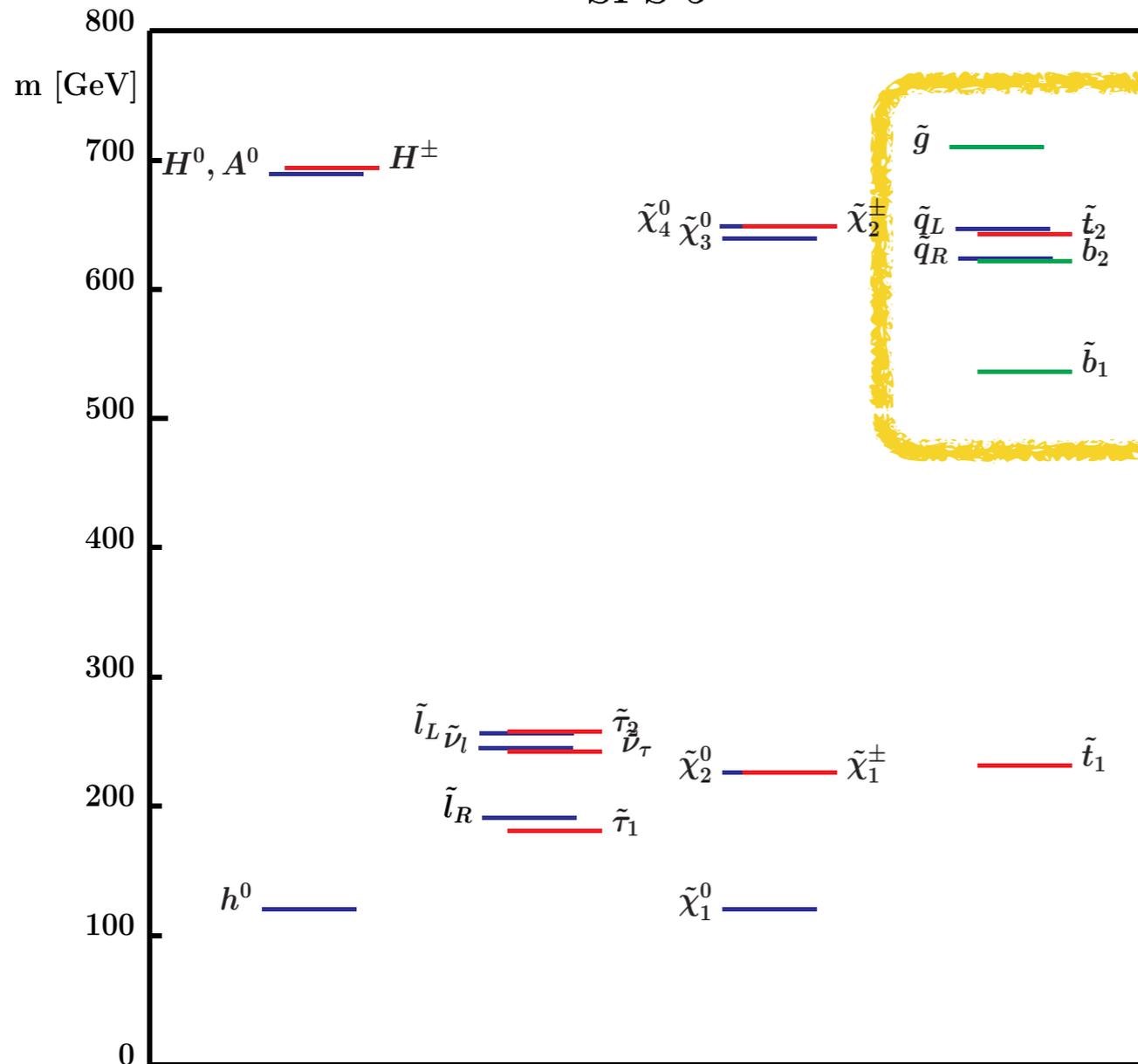
similar mass for all squark generations & gluino

color neutral particles hovering right at the 100-200

[LesHouches 2011]

# what was possible in SUSY, a la 2010

SPS 5



CMSSM-style spectra

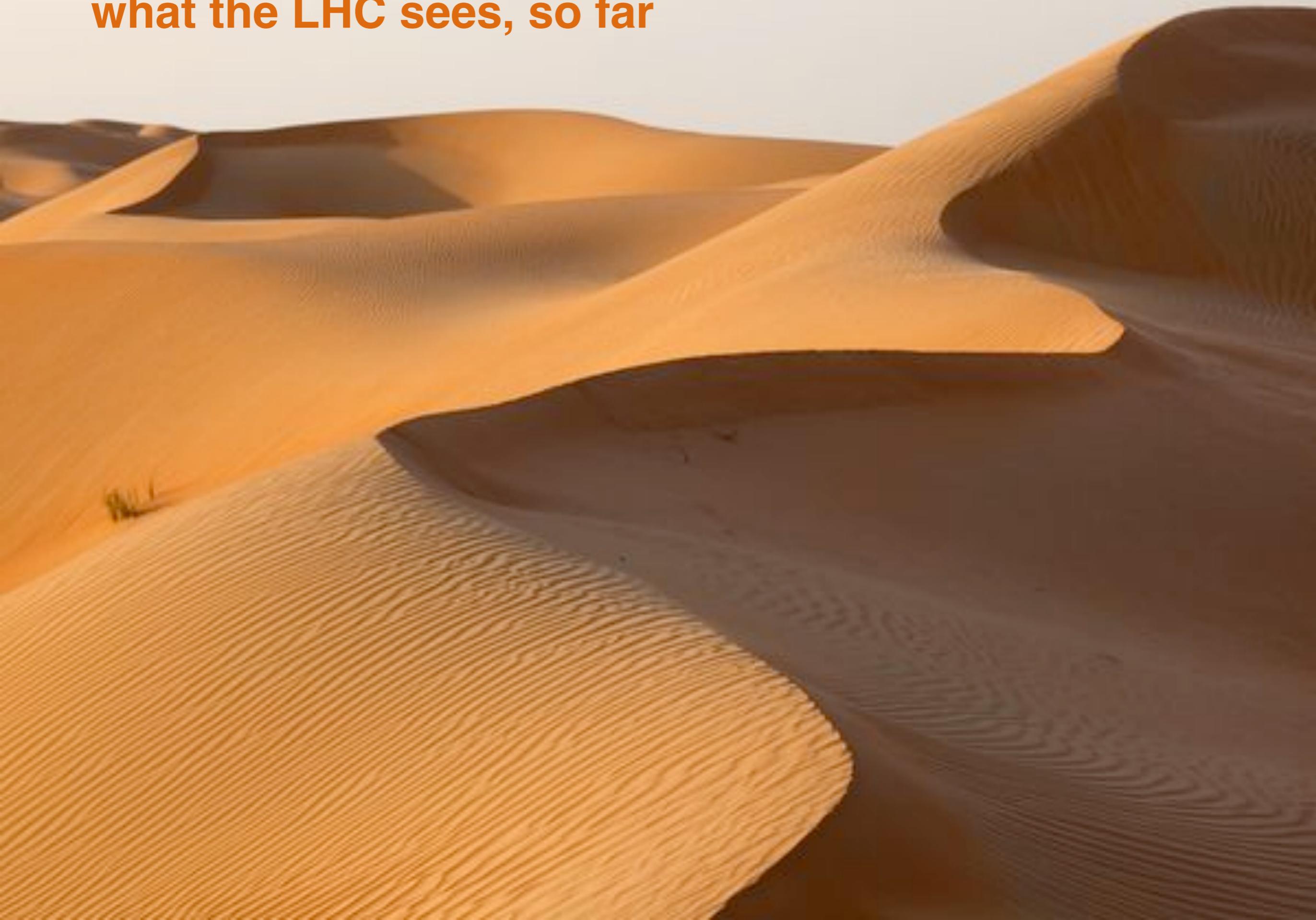
colored sparticles  $\approx 1000$  GeV,

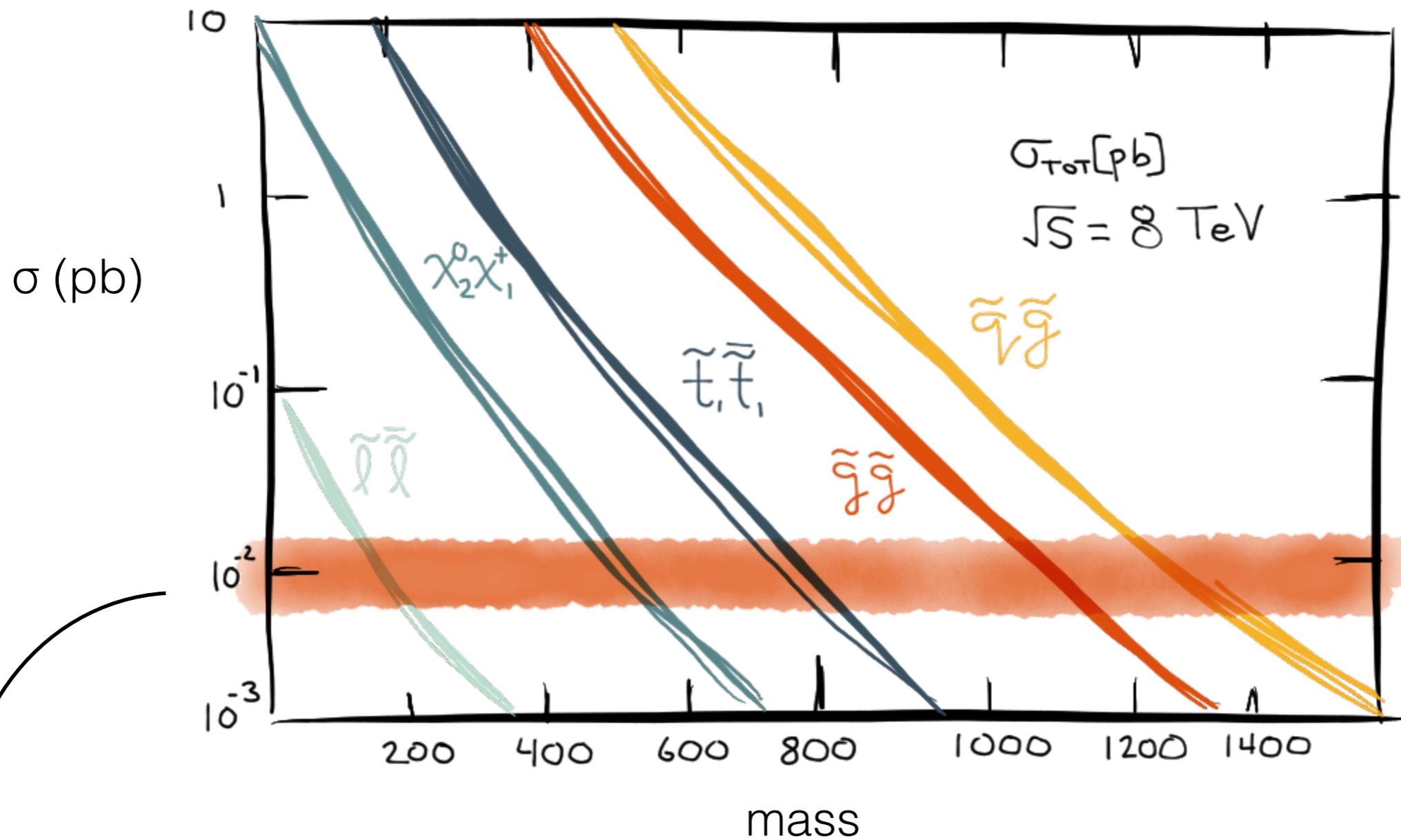
similar mass for all squark  
generations & gluino

color neutral particles hovering  
right at the 100-200

[LesHouches 2011]

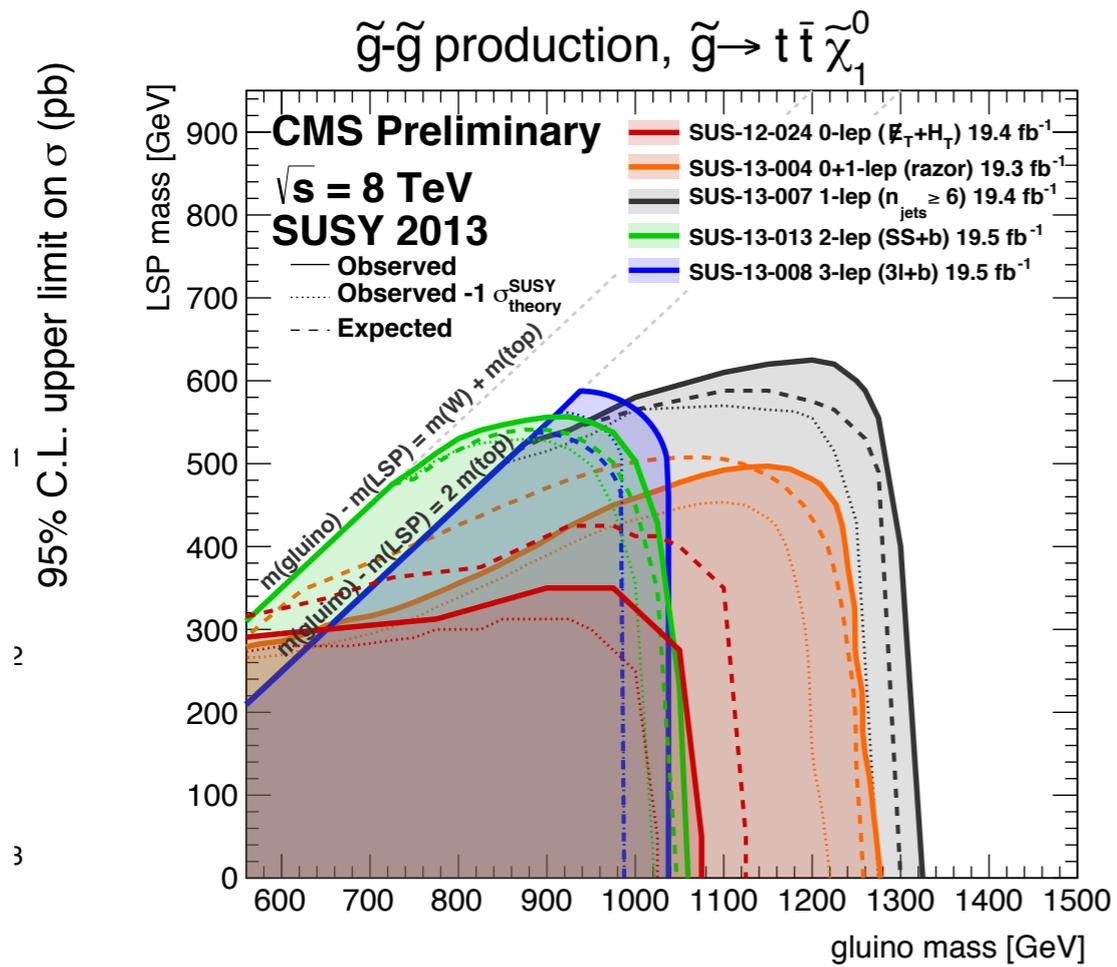
**what the LHC sees, so far**



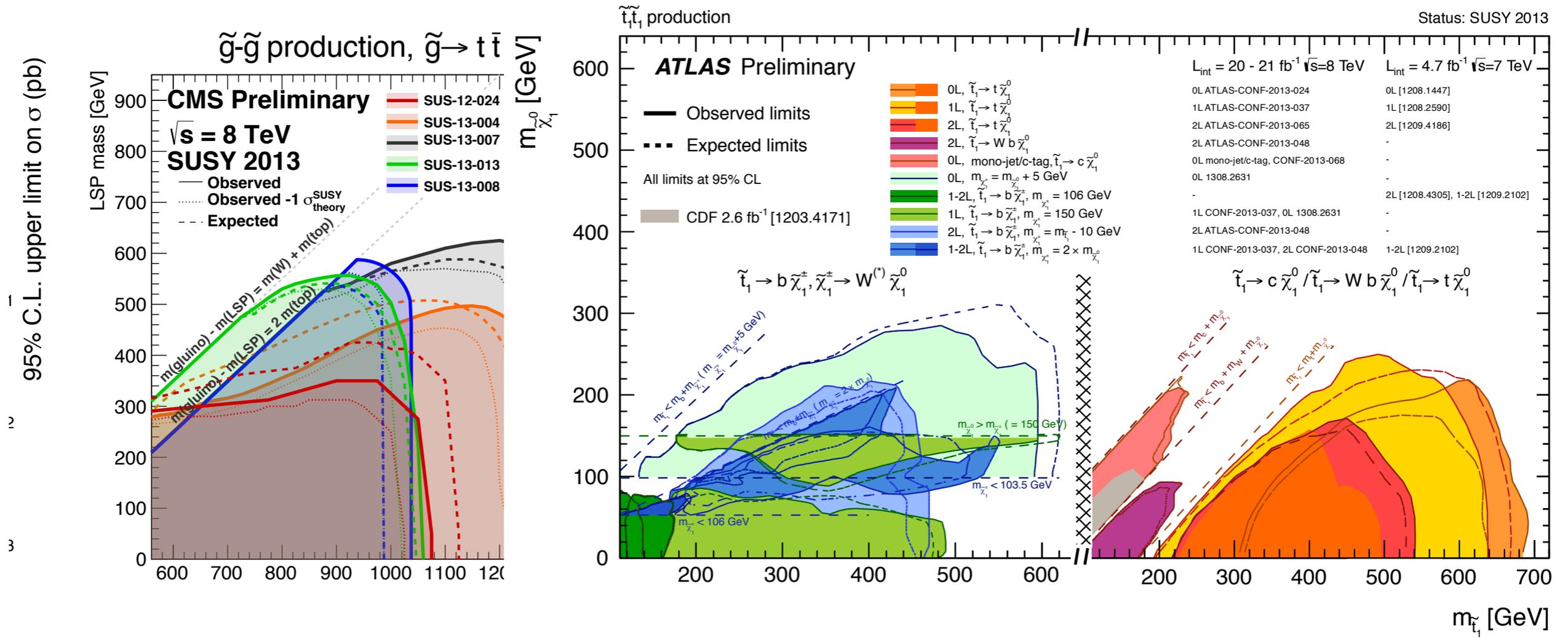


'typical' cross sections for supersymmetry processes  
 rough limits after LHC<sub>8</sub> :  $\sigma \sim 10$  fb

more detailed limits: some dependence on decays



# more detailed limits: some dependence on decays







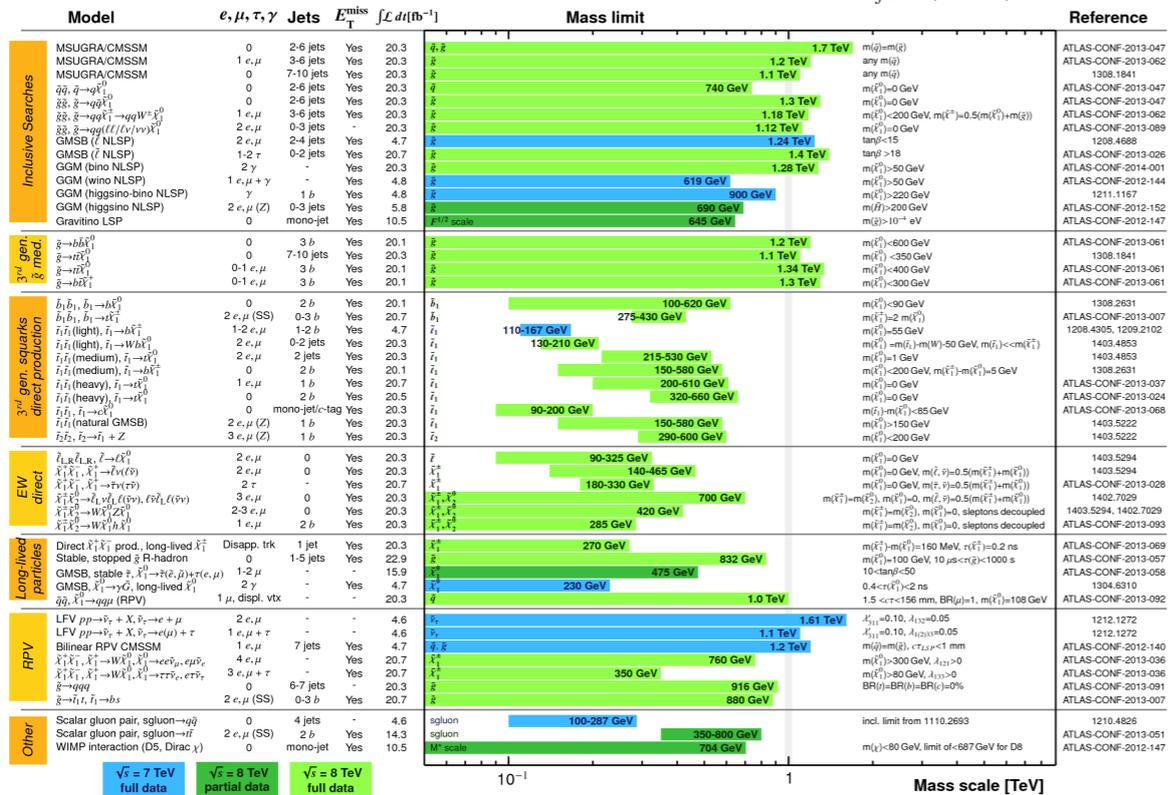


the only stop seen at CERN



BUT:

limits are driven by first generation squarks... not the most important states for EWSB

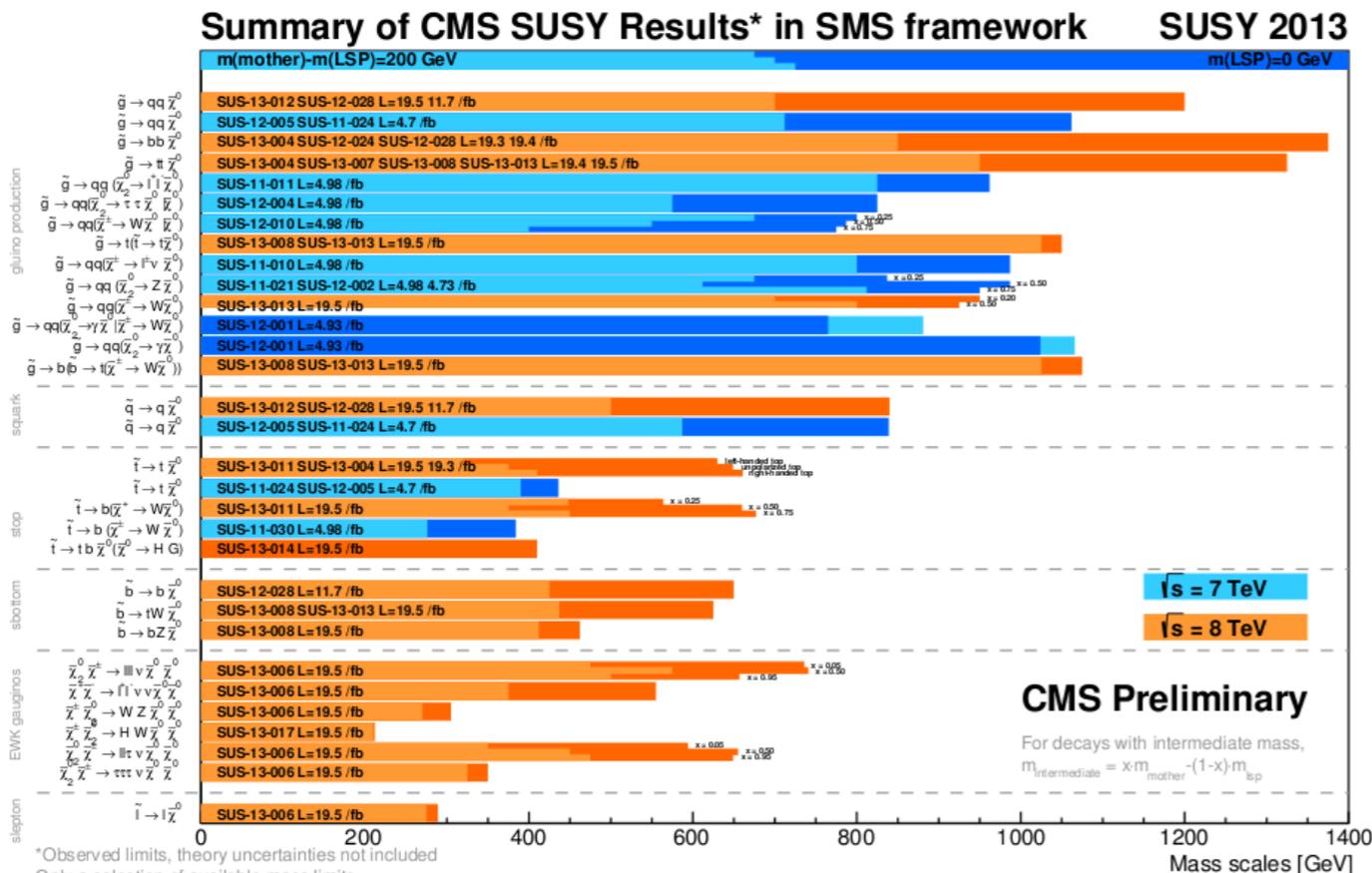


\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

what do we need to be light?

and

what do we need (analysis-wise, machine wise) to see those states?



CMS Preliminary

For decays with intermediate mass,  $m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{sp}$

\*Observed limits, theory uncertainties not included  
Only a selection of available mass limits  
Probe \*up to\* the quoted mass limit

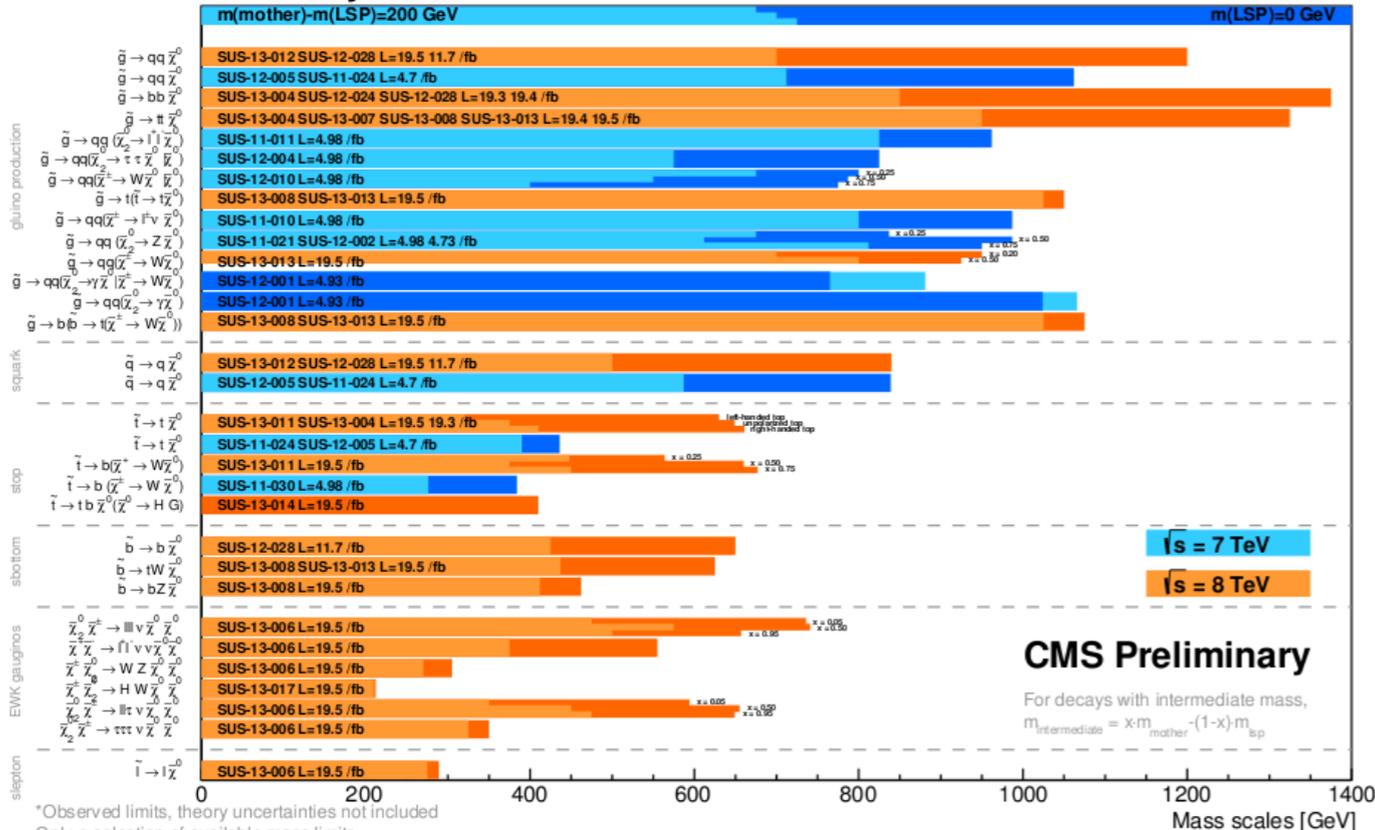
BUT:

Model	$e, \mu, \tau, \gamma$	Jets	$E_{T}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{q}$ 1.7 TeV	ATLAS-CONF-2013-047	
	MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}, \tilde{q}$ 1.2 TeV	ATLAS-CONF-2013-062	
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}, \tilde{q}$ 1.1 TeV	1308.1841	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 740 GeV	ATLAS-CONF-2013-047	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	ATLAS-CONF-2013-047	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	ATLAS-CONF-2013-062	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	2 $e, \mu$	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	ATLAS-CONF-2013-069	
	GMSB ( $\tilde{t}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	1208.4688	
	GMSB ( $\tilde{t}$ NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	ATLAS-CONF-2013-026	
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	ATLAS-CONF-2014-001	
$3^{\text{rd}}$ gen. & med.	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	ATLAS-CONF-2013-061	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	1308.1841	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	ATLAS-CONF-2013-061	
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	ATLAS-CONF-2013-061	
	$3^{\text{rd}}$ gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{t}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 100-620 GeV	1308.2631
		$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{t}_1$ 275-430 GeV	ATLAS-CONF-2013-007
		$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{t}_1^0$	1-2 $e, \mu$	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	1208.4305, 1209.2102
		$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{t}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	1403.4853
		$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	1403.4853
		$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{t}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	1308.2631
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$		1 $e, \mu$	1 b	Yes	20.7	$\tilde{t}_1$ 200-510 GeV	ATLAS-CONF-2013-037	
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{t}_1^0$		0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	ATLAS-CONF-2013-024	
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)		2 $e, \mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	ATLAS-CONF-2013-068	
$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$		3 $e, \mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	1403.5222	
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{t}_1$ 90-325 GeV	1403.5294	
	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{t}_1$ 140-465 GeV	1403.5294	
	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2 $\tau$	0	Yes	20.7	$\tilde{t}_1$ 180-330 GeV	ATLAS-CONF-2013-028	
	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	3 $e, \mu$	0	Yes	20.3	$\tilde{t}_1$ 700 GeV	1402.7029	
	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	2-3 $e, \mu$	0	Yes	20.3	$\tilde{t}_1$ 420 GeV	1403.5294, 1402.7029	
	$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\tilde{t}_1^0$	1 $e, \mu$	2 b	Yes	20.3	$\tilde{t}_1$ 285 GeV	ATLAS-CONF-2013-093	
	Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod. long-lived $\tilde{t}_1^+$	Disapp. trk	1 jet	Yes	20.3	$\tilde{t}_1$ 270 GeV	ATLAS-CONF-2013-068
		Stable, stopped $\tilde{t}_1$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{t}_1$ 832 GeV	ATLAS-CONF-2013-057
		GMSB stable $\tilde{t}_1$ $\tilde{t}_1 \rightarrow \tilde{t}_1^0 + (e, \mu)$	1-2 $\mu$	-	-	15.9	$\tilde{t}_1$ 475 GeV	ATLAS-CONF-2013-058
		GMSB $\tilde{t}_1 \rightarrow G$ , long-lived $\tilde{t}_1^+$	2 $\gamma$	-	Yes	4.7	$\tilde{t}_1$ 230 GeV	1304.6310
$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1 \rightarrow q\tilde{q}$ (RPV)		1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{g}$ 1.0 TeV	ATLAS-CONF-2013-092	
RPV		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	1212.1272
		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	1212.1272
		Bilinear RPV CMSSM	1 $e, \mu$	7 jets	Yes	4.7	$\tilde{g}, \tilde{q}$ 1.2 TeV	ATLAS-CONF-2012-140
		$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{t}_1^0, \tilde{t}_1\tilde{t}_1 \rightarrow e\tilde{\nu}_e, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.7	$\tilde{t}_1$ 760 GeV	ATLAS-CONF-2013-036
		$\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{t}_1^0, \tilde{t}_1\tilde{t}_1 \rightarrow \tau\tilde{\nu}_\tau, e\tau\tilde{\nu}_e$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{t}_1$ 350 GeV	ATLAS-CONF-2013-036
	$\tilde{t}_1\tilde{t}_1 \rightarrow q\tilde{q}$	2 $e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{t}_1$ 916 GeV	ATLAS-CONF-2013-091	
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{s}$	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV	ATLAS-CONF-2013-007	
	Other	Scalar gluon pair, $g\text{gluon} \rightarrow q\tilde{q}$	0	4 jets	-	4.6	gluon 100-287 GeV	1210.4826
		Scalar gluon pair, $g\text{gluon} \rightarrow t\tilde{t}$	2 $e, \mu$ (SS)	2 b	Yes	14.3	gluon 350-800 GeV	ATLAS-CONF-2013-051
		WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$\tilde{t}_1$ scale 704 GeV	ATLAS-CONF-2012-147

limits have holes

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

Summary of CMS SUSY Results\* in SMS framework SUSY 2013



what do we need (analysis-wise, machine wise) to fill these gaps

\*Observed limits, theory uncertainties not included  
Only a selection of available mass limits  
Probe \*up to\* the quoted mass limit

# Naturalness

$$\frac{1}{2}M_Z^2 = -m_{H_u}^2 - |\mu|^2 + O\left(\frac{1}{\tan^2 \beta}\right)$$

# Naturalness

$$\frac{1}{2}M_Z^2 = -m_{H_u}^2 - |\mu|^2 + O\left(\frac{1}{\tan^2 \beta}\right)$$

$$\Delta(|\mu|^2) = 10 \times \frac{|\mu|^2}{(200 \text{ GeV})^2} \quad \text{“tree-level”}$$

$$\begin{aligned} \Delta(\delta m_{H_u}^2 |_{\text{stop}}) &= \frac{3y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log \frac{\Lambda_{\text{mess}}}{(m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}} \\ &\simeq 10 \times \frac{m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2}{2 \times (450 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}} / (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}}{3} . \end{aligned}$$

“loop-level”

# Naturalness

$$\frac{1}{2} M_Z^2 = -m_{H_u}^2 - |\mu|^2 + O\left(\frac{1}{\tan^2 \beta}\right)$$

$$\Delta(|\mu|^2) = 10 \times \frac{|\mu|^2}{(200 \text{ GeV})^2} \quad \text{“tree-level”}$$

$$\begin{aligned} \Delta(\delta m_{H_u}^2 |_{\text{stop}}) &= \frac{3y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log \frac{\Lambda_{\text{mess}}}{(m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}} \\ &\simeq 10 \times \frac{m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2}{2 \times (450 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}} / (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}}{3} . \end{aligned}$$

“loop-level”

small  $\Delta$  pushes for

$$\mu \sim 100\text{-}200 \text{ GeV}$$

$$m_{\text{stop}} \sim 400 \text{ GeV}$$

# Naturalness

$$\Delta(\delta m_{H_u}^2 |_{\text{wino}}) = \frac{3g_2^2}{8\pi^2} |M_2|^2 \log \frac{\Lambda_{\text{mess}}}{|M_2|}$$

scale where SUSY-breaking communicated

$$\simeq 10 \times \frac{|M_2|^2}{(930 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}} / |M_2|}{3}$$

$$\Delta(\delta m_{H_u}^2 |_{\text{gluino}}) = \frac{2\alpha_s y_t^2}{\pi^3} |M_3|^2 \log \frac{\Lambda_{\text{mess}}}{(m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}} \log \frac{\Lambda_{\text{mess}}}{|M_3|}$$

$$= 10 \times \frac{|M_3|^2}{(1200 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}} / (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}}{3} \frac{\log \Lambda_{\text{mess}} / |M_3|}{1.5}$$

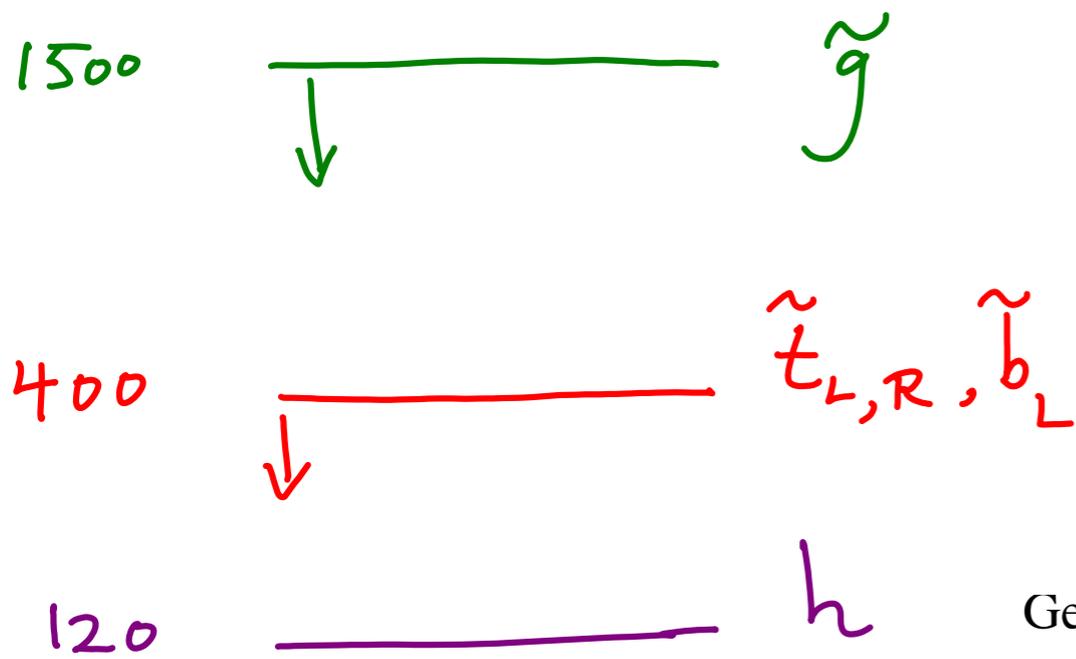
wino:  $\lesssim$  TeV

gluino:  $\lesssim$  1.3 TeV, comes from stop running

same sparticles affect Higgs mass, but weaker dependence

# Naturalness

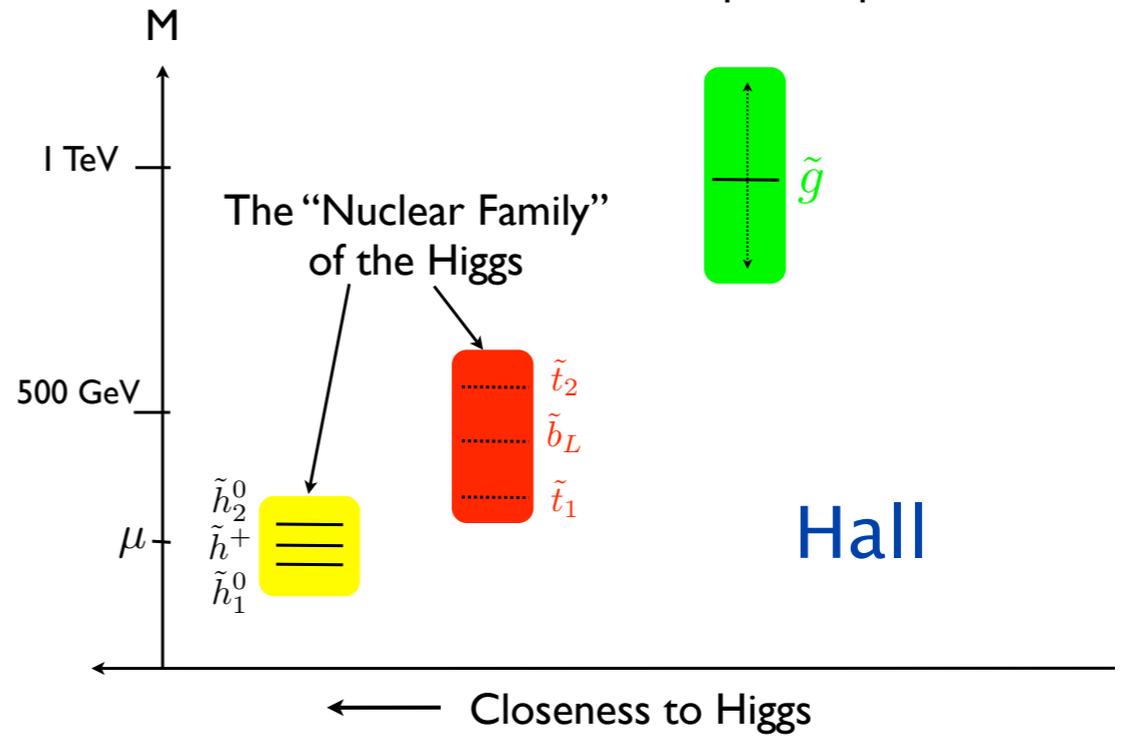
Compulsory Natural SUSY



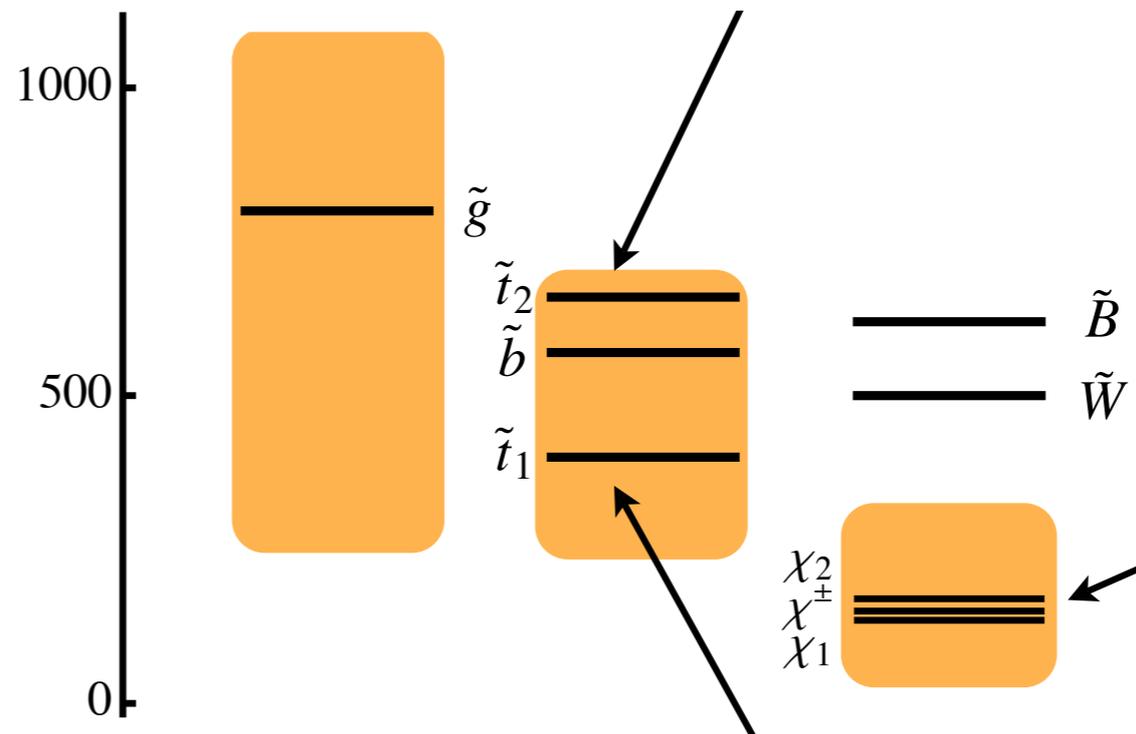
Arkani-Hamed

## A Natural Spectrum

General "bottom-up" viewpoint



GeV

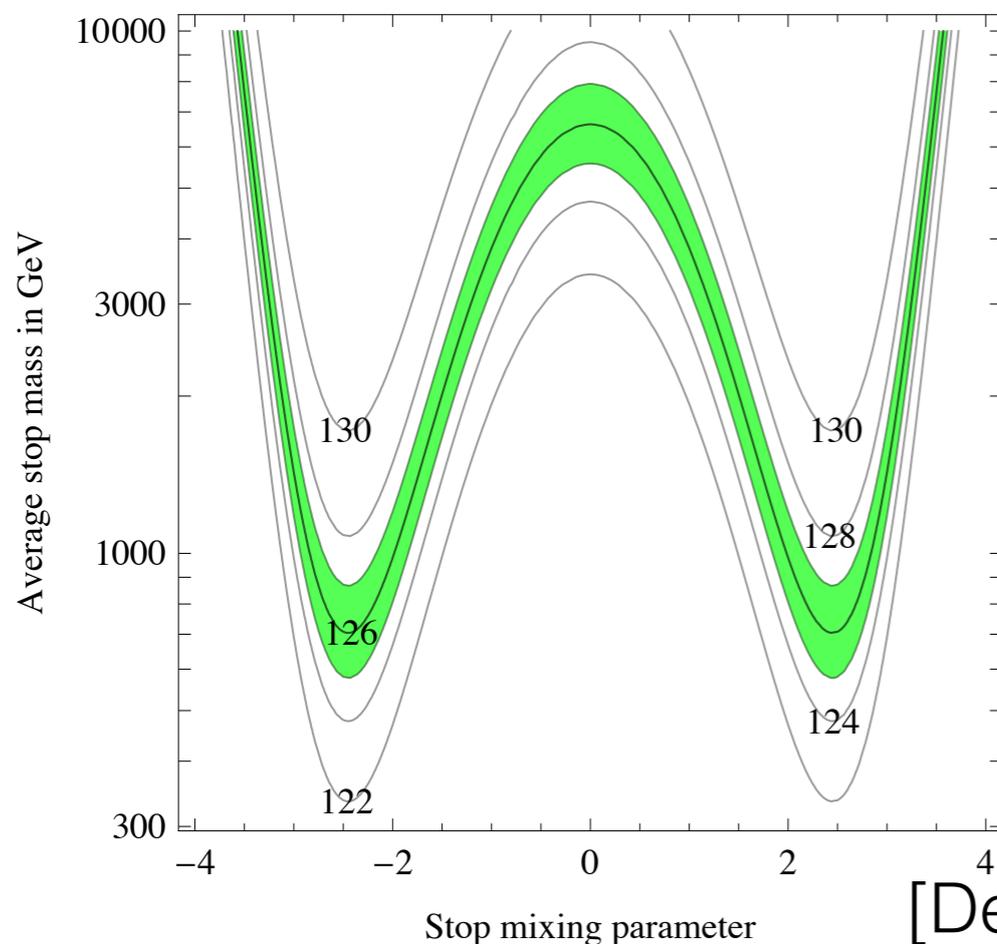


Barbieri

even without direct limits, a dose of reality

Higgs mass forces **MSSM** supersymmetry to shift expectations

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta y_t^2 \left[ m_t^2 \ln \left( m_{\tilde{t}_1} m_{\tilde{t}_2} / m_t^2 \right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right. \\ \left. + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2} (m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right\} / m_t^2 \right].$$



only log-sensitive to superpartner masses

large increase in stop mass  
 -> **small**  $m_h$  increase,  
 but **large** increase in  $\Delta$

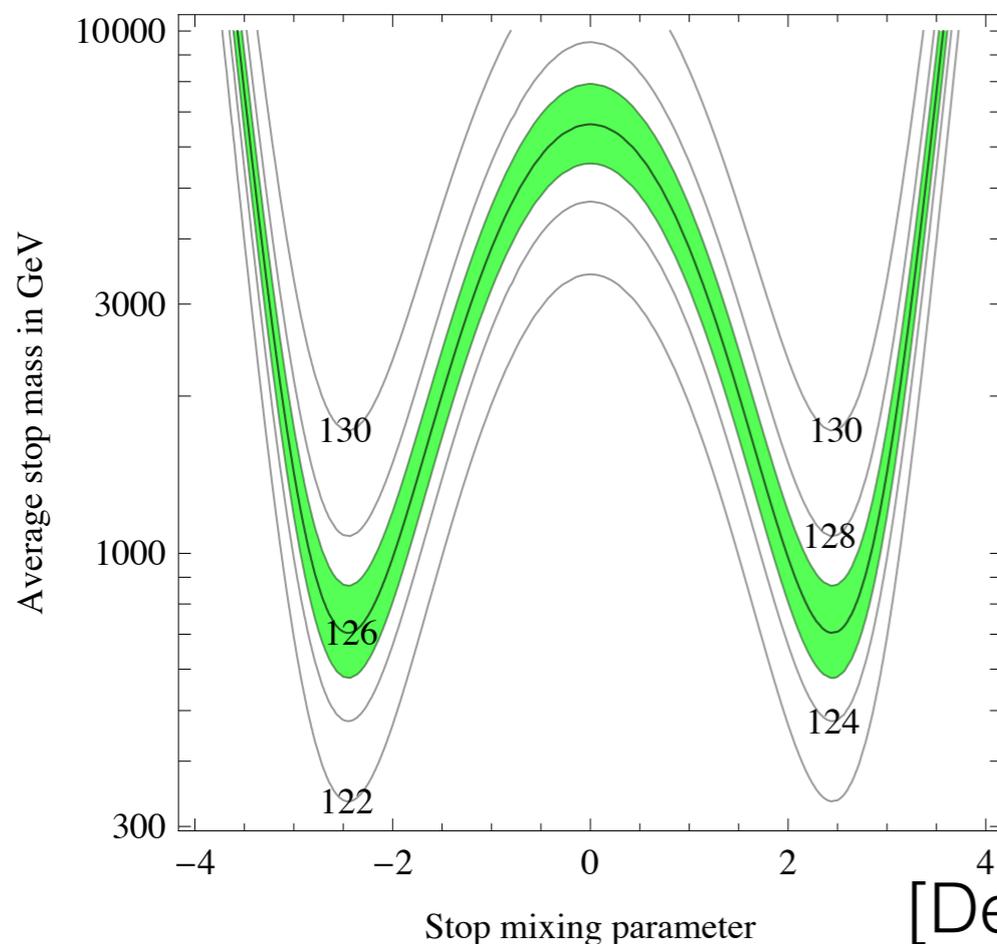
[Delgado et al '12]

even without direct limits, a dose of reality

*though fairly easy to accommodate in extended setups*

Higgs mass forces **MSSM** supersymmetry to shift expectations

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta y_t^2 \left[ m_t^2 \ln \left( m_{\tilde{t}_1} m_{\tilde{t}_2} / m_t^2 \right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2} (m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right\} / m_t^2 \right].$$



only log-sensitive to superpartner masses

large increase in stop mass  
 -> **small**  $m_h$  increase,  
 but **large** increase in  $\Delta$

[Delgado et al '12]

even without direct limits, a dose of reality

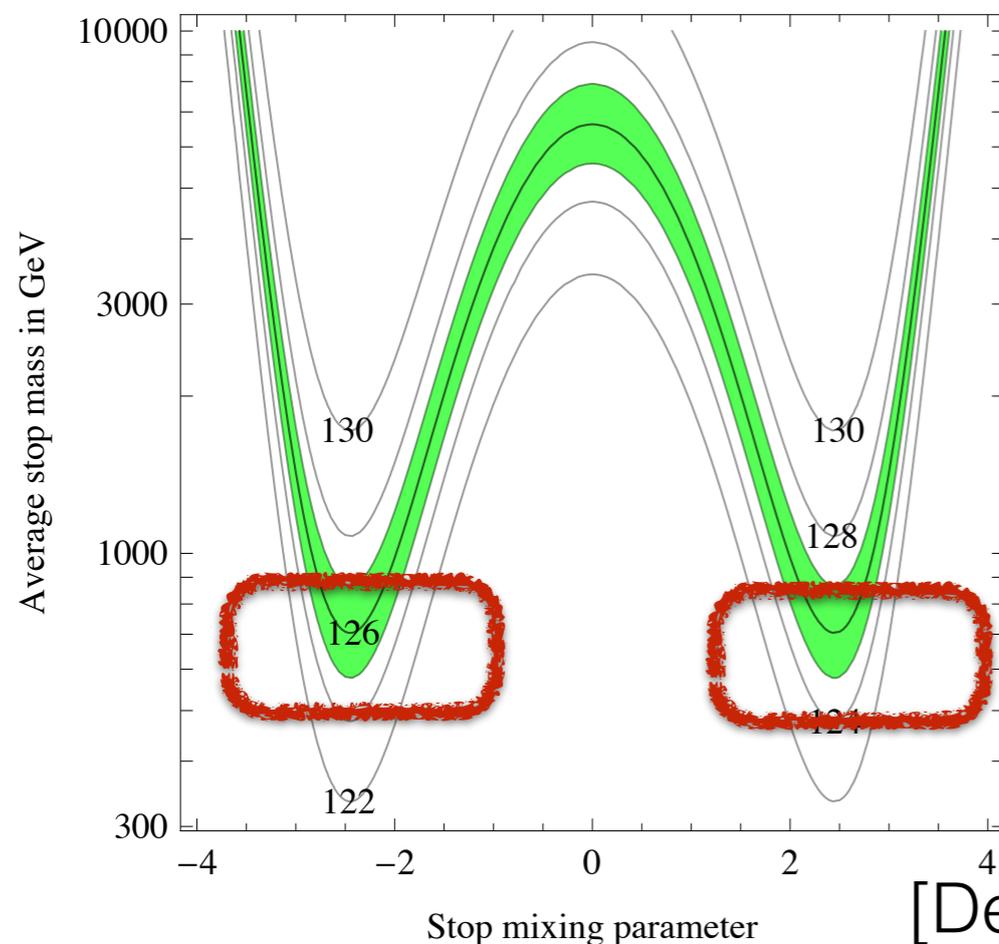
*though fairly easy to accommodate in extended setups*

Higgs mass forces **MSSM** supersymmetry to shift expectations

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta y_t^2 \left[ m_t^2 \ln \left( m_{\tilde{t}_1} m_{\tilde{t}_2} / m_t^2 \right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2} (m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right\} / m_t^2 \right].$$

only log-sensitive to superpartner masses

large increase in stop mass  
 -> **small**  $m_h$  increase,  
 but **large** increase in  $\Delta$



[Delgado et al '12]

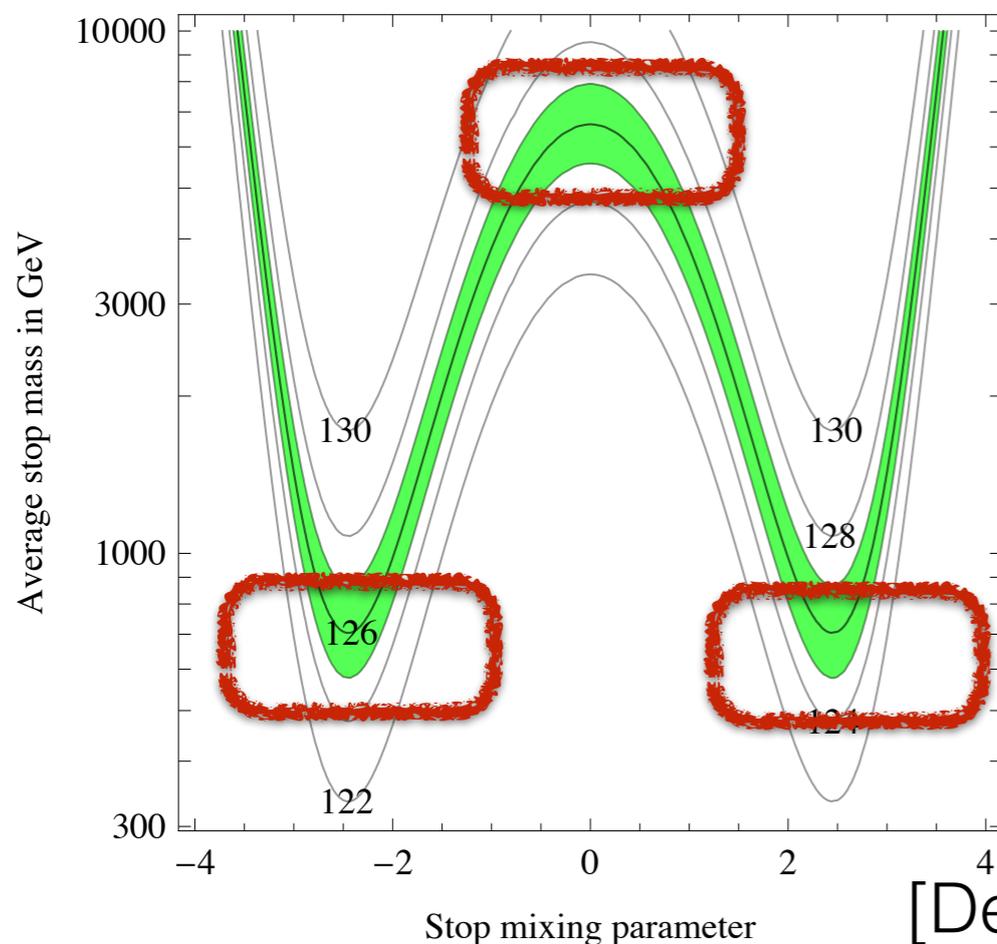
even without direct limits, a dose of reality

*though fairly easy to accommodate in extended setups*

Higgs mass forces **MSSM** supersymmetry to shift expectations

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta y_t^2 \left[ m_t^2 \ln \left( m_{\tilde{t}_1} m_{\tilde{t}_2} / m_t^2 \right) + c_t^2 s_t^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right. \\ \left. + c_t^4 s_t^4 \left\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2} (m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2 / m_{\tilde{t}_1}^2) \right\} / m_t^2 \right].$$

only log-sensitive to superpartner masses



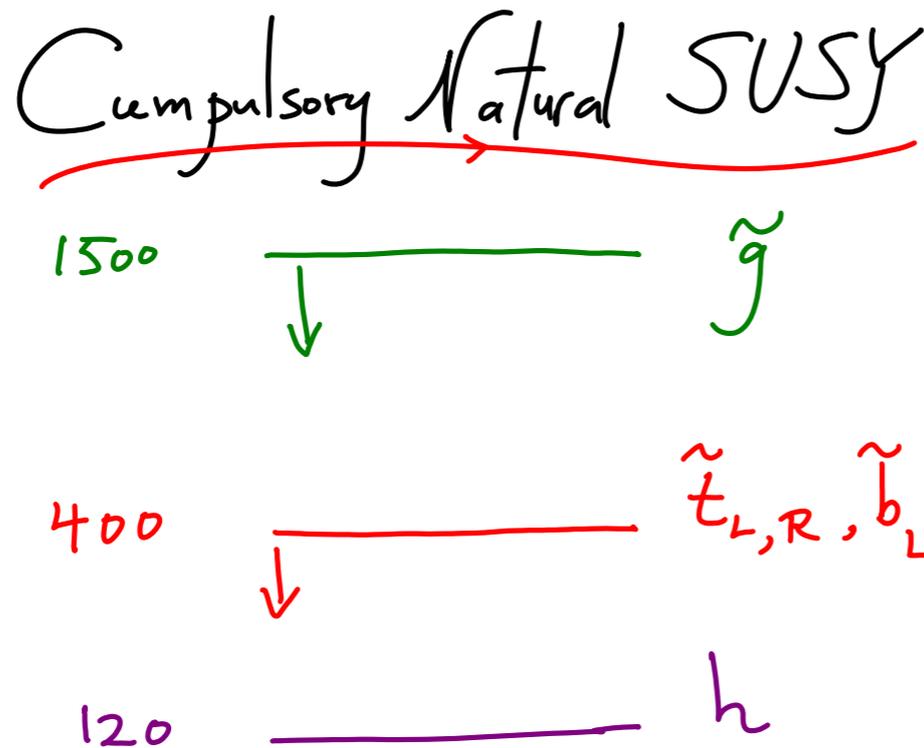
[Delgado et al '12]

large increase in stop mass  
-> **small**  $m_h$  increase,  
but **large** increase in  $\Delta$

# targeting natural SUSY

Higgs mass makes us accept more tuning, but the **natural paradigm remains relatively unconstrained**

## Number 1 SUSY target for LHC<sub>14</sub> + beyond



model building efforts well underway

[Craig et al '11, '12],

[Delgado et al '11]

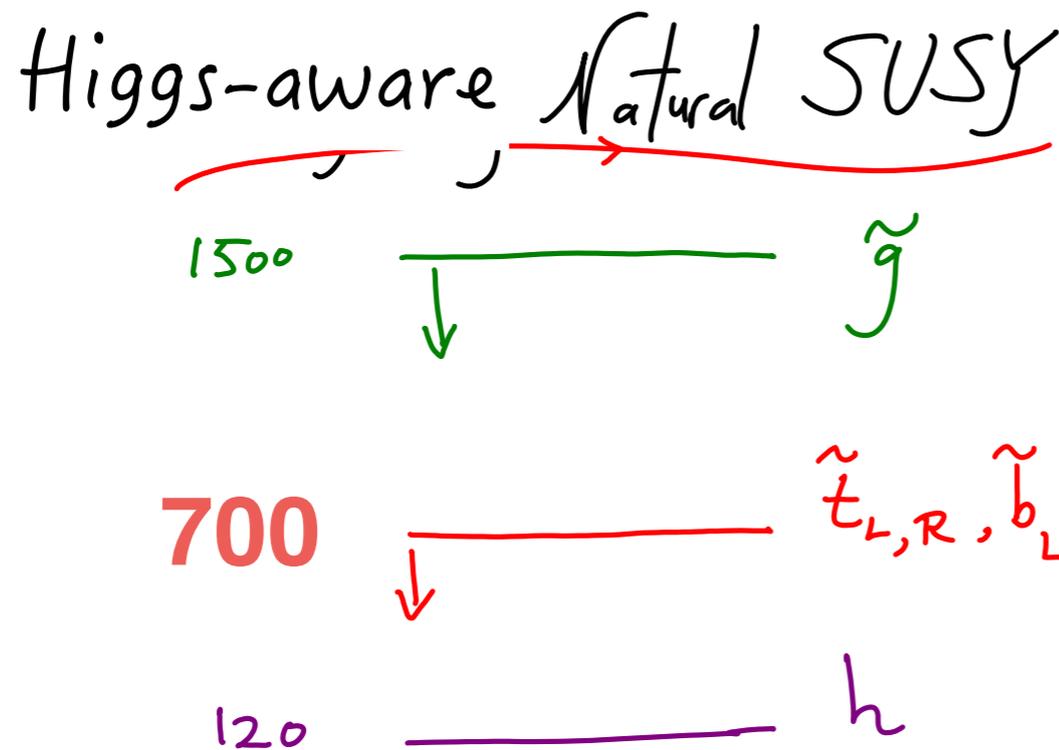
lightest states are the Higgsinos ( $\mu$ ) and stops

(gluino contribution more model dependent.. (e.g. Dirac SUSY))

# targeting natural SUSY

Higgs mass makes us accept more tuning, but the **natural paradigm remains relatively unconstrained**

## Number 1 SUSY target for LHC<sub>14</sub> + beyond



model building efforts well underway

[Craig et al '11, '12],

[Delgado et al '11]

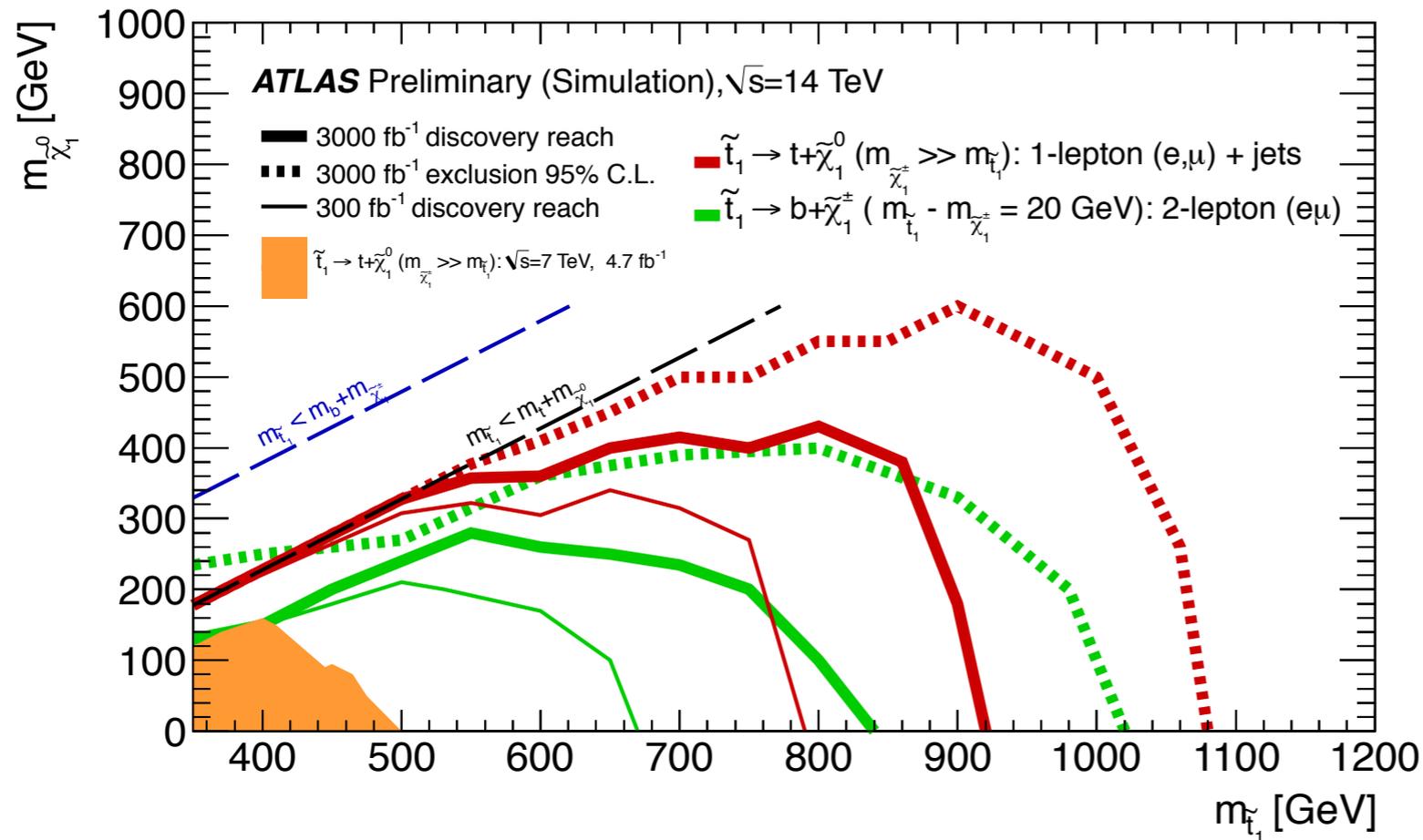
lightest states are the Higgsinos ( $\mu$ ) and stops

(gluino contribution more model dependent.. (e.g. Dirac SUSY))

stops

Higgs mass **already** tells us stops (either one or both) should be  $> \text{TeV}$  (within vanilla MSSM).

LHC reach estimate [Eur. Strategy book, 2013]



region where we need to get is where the LHC is running out of steam...

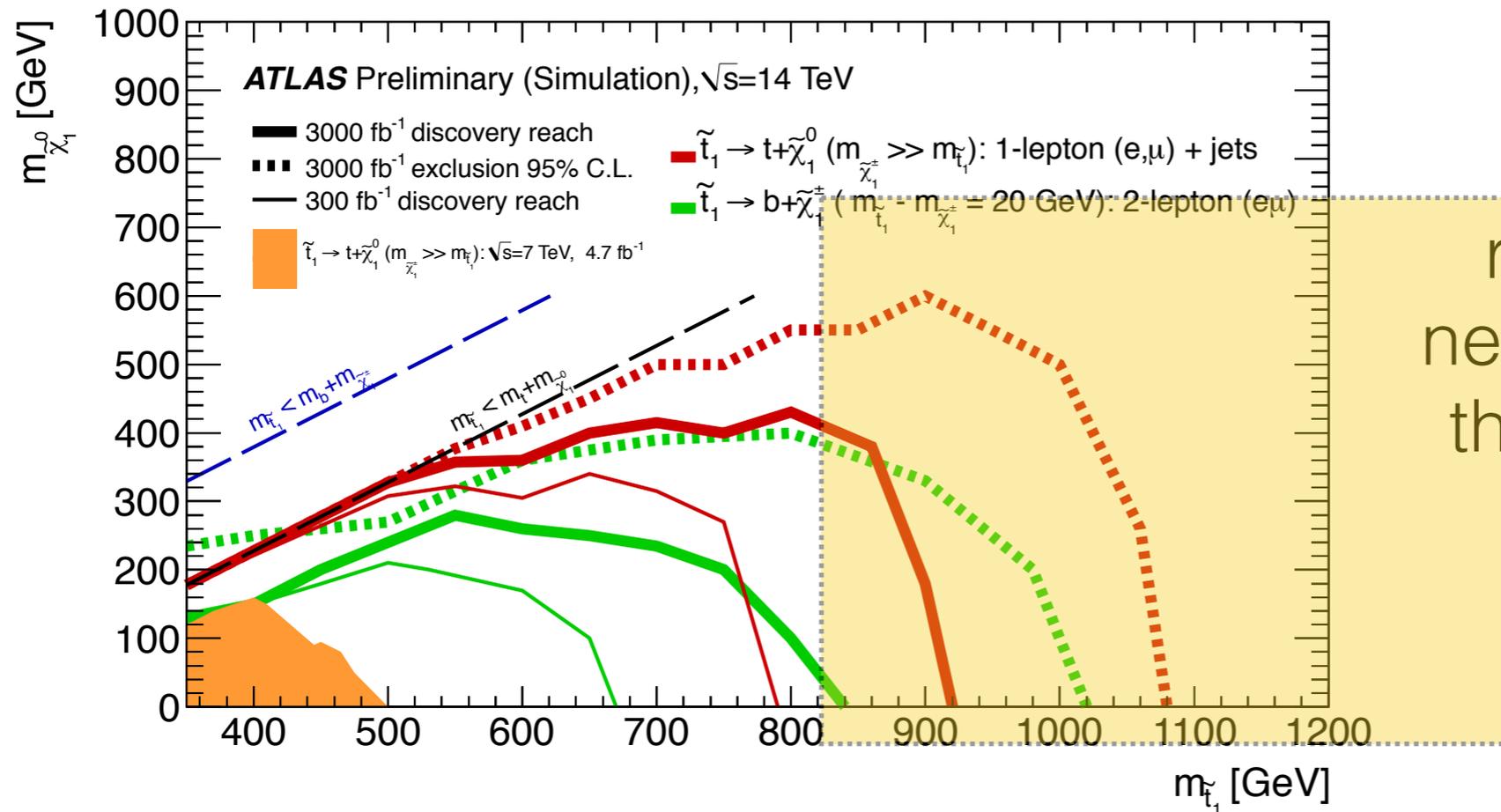
future collider should have **this** region in its sights

want to study the stop, not just discover it!!

stops

Higgs mass **already** tells us stops (either one or both) should be  $> \text{TeV}$  (within vanilla MSSM).

LHC reach estimate [Eur. Strategy book, 2013]



future collider should have **this** region in its sights

want to study the stop, not just discover it!!

lots of tricks that allow lighter stops (and other states) to remain valid

- R-parity violation
- long cascade decays
- compressed spectra

lots of tricks that allow lighter stops (and other states) to remain valid

- R-parity violation
- long cascade decays
- compressed spectra

kills the MET signal by having the LSP decay to SM

spreads out energy over multiple final state objects, making them too soft for cuts

limits the phase space for decay particles, lowering the average energy and the MET

lots of tricks that allow lighter stops (and other states) to remain valid

- R-parity violation
- long cascade decays
- compressed spectra

clean environment and knowledge of initial state means lepton colliders are not confused by these tricks: 'loophole free'  
[Berggren 1308.1461]

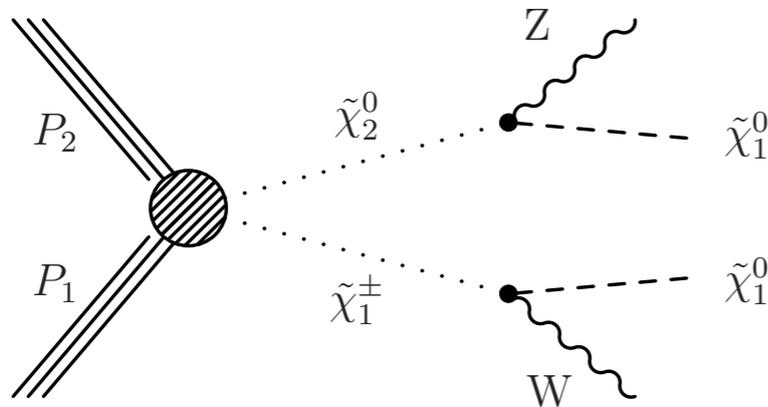
plus offer unparalleled precision in mass/mass-difference/spin/coupling measurements (though fewer recent/detailed studies done for  $\mu$ -collider)

**to take advantage of these benefits, need the energy to make the sparticles:  $\mu$ -collider**

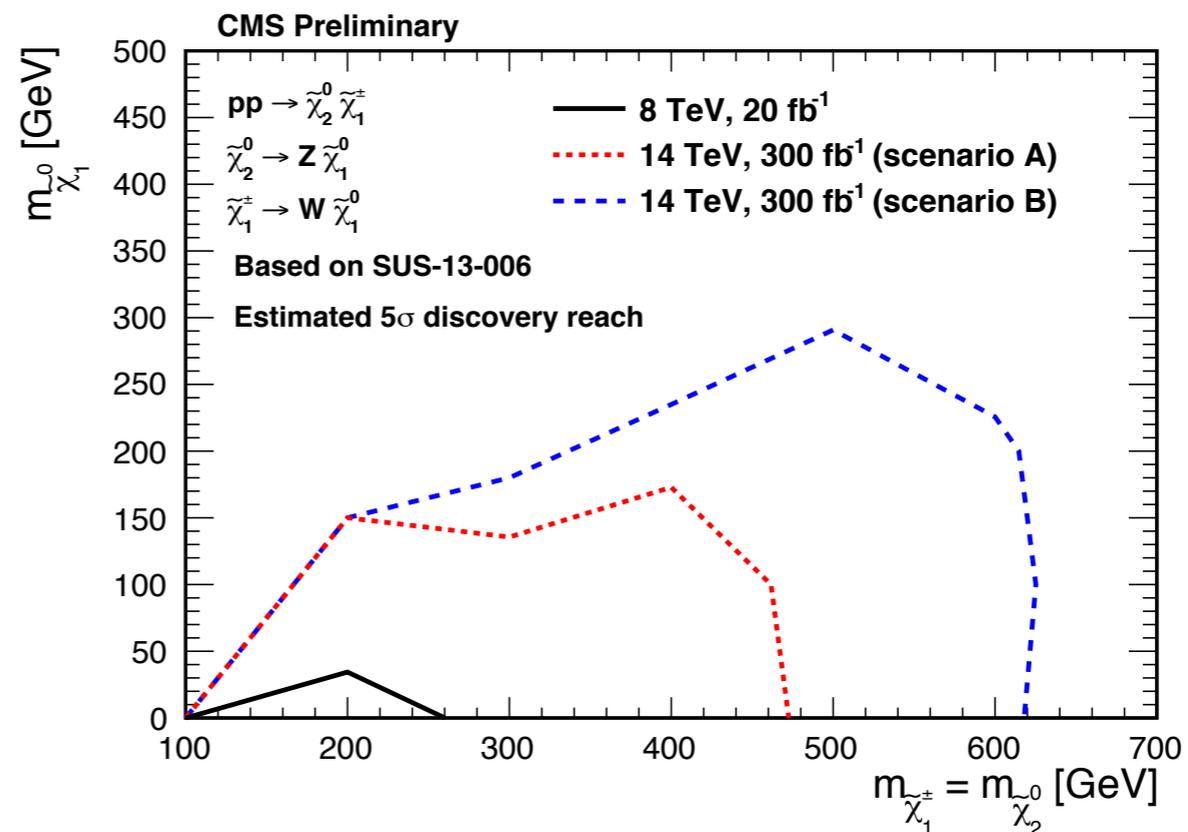
# light electroweakinos (Higgsinos/Winos/Bino)

$\mu$  must be light for naturalness  $\rightarrow$  **prime** target for LHC/future collider studies

in some SUSY setups, i.e. **split SUSY**, electroweakinos are the only TeV-scale particles, **motivated by DM & unification**



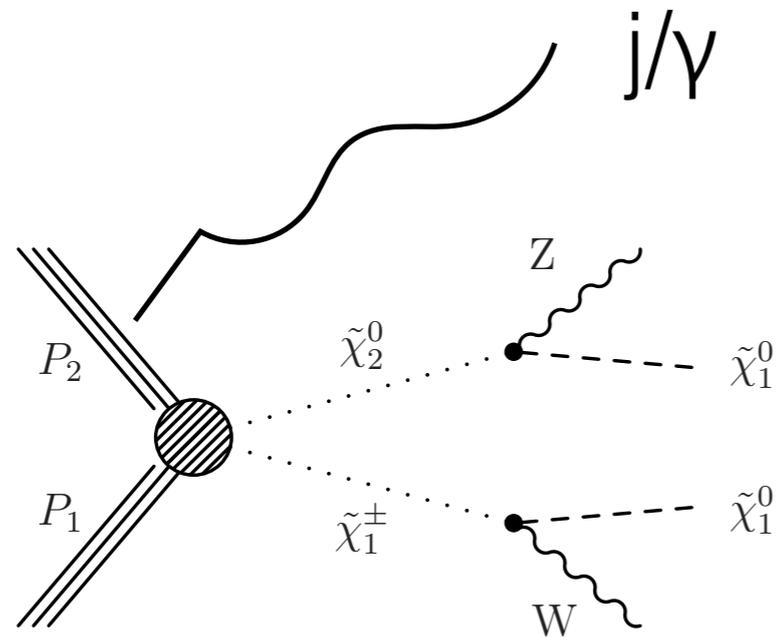
[CMS 1307.7135]



electroweakino mixtures can be as heavy as  **$\sim 3$  TeV** while remaining viable DM candidates... well beyond reach of LHC/ILC

chargino searches lose sensitivity as mass increases or mass splitting decreases

when states are nearly degenerate, must rely on ISR-assisted signals

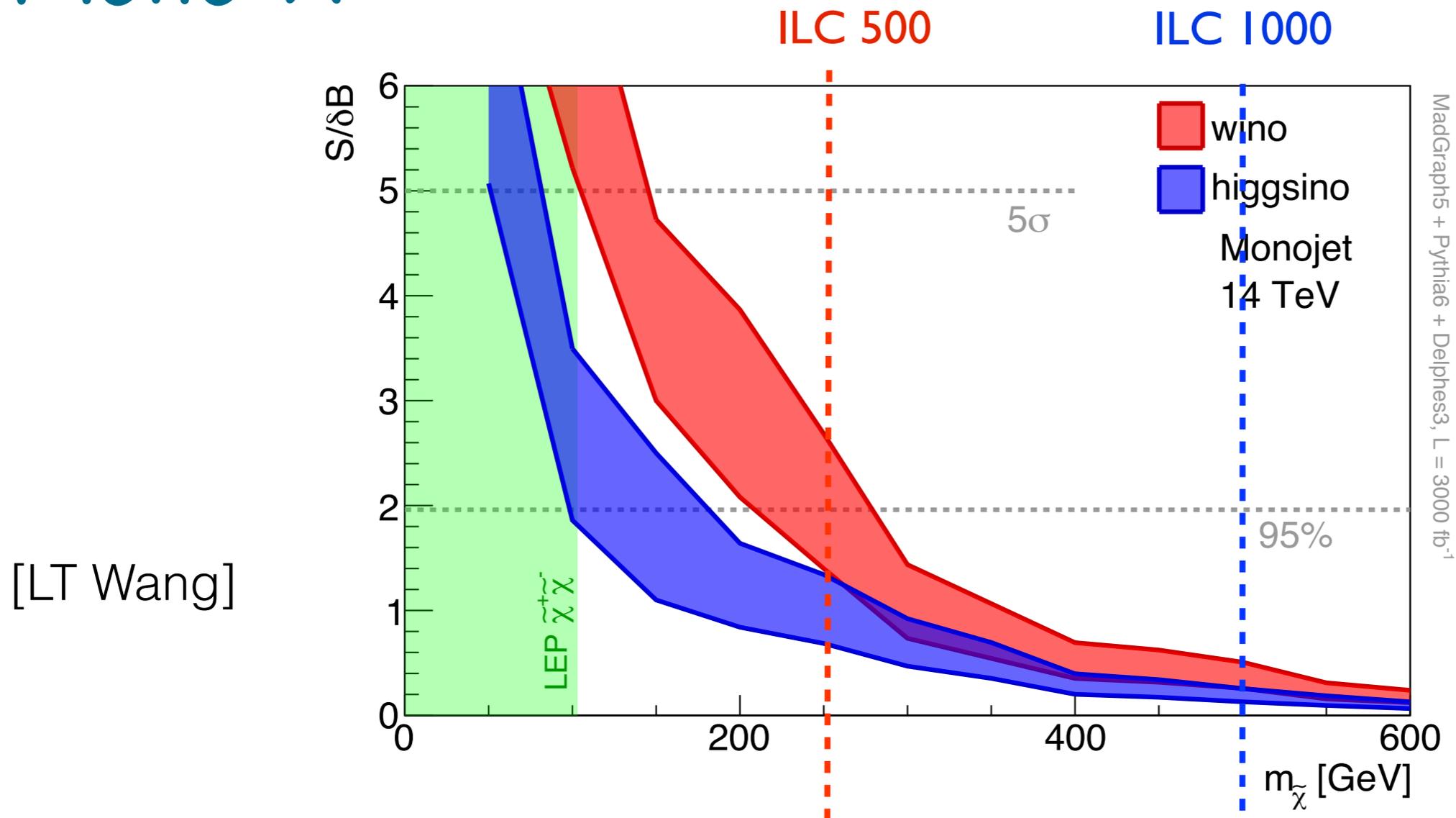


tricky at LHC due to systematics on  $Z(\nu\bar{\nu})+j/\gamma$  background,

- $\sim$  no limit at LHC<sub>8</sub>
- limited reach even after several  $\text{ab}^{-1}$ , LHC<sub>14</sub>

chargino searches lose sensitivity as mass increases or mass splitting decreases

## Mono-X



ILC sensitivity near  $\sqrt{s}/2$ .. no  $\mu$ -collider study I know of

neutralino/chargino spectrum contains a lot of information about  
the theory ( $\mu$ ,  $M_1$ ,  $M_2$ ,  $\tan\beta$ )

full sector must be observed to distinguish between models

current 'standard' searches focus on  $\chi^\pm\chi^0_2$

**many extensions of the MSSM (i.e NMSSM) leave their  
most visible imprint in the EW-ino sector as extra states  
or modified interactions**

precision, high energy studies necessary

s-channel advantage:

all SUSY models contain extra Higgses H/A

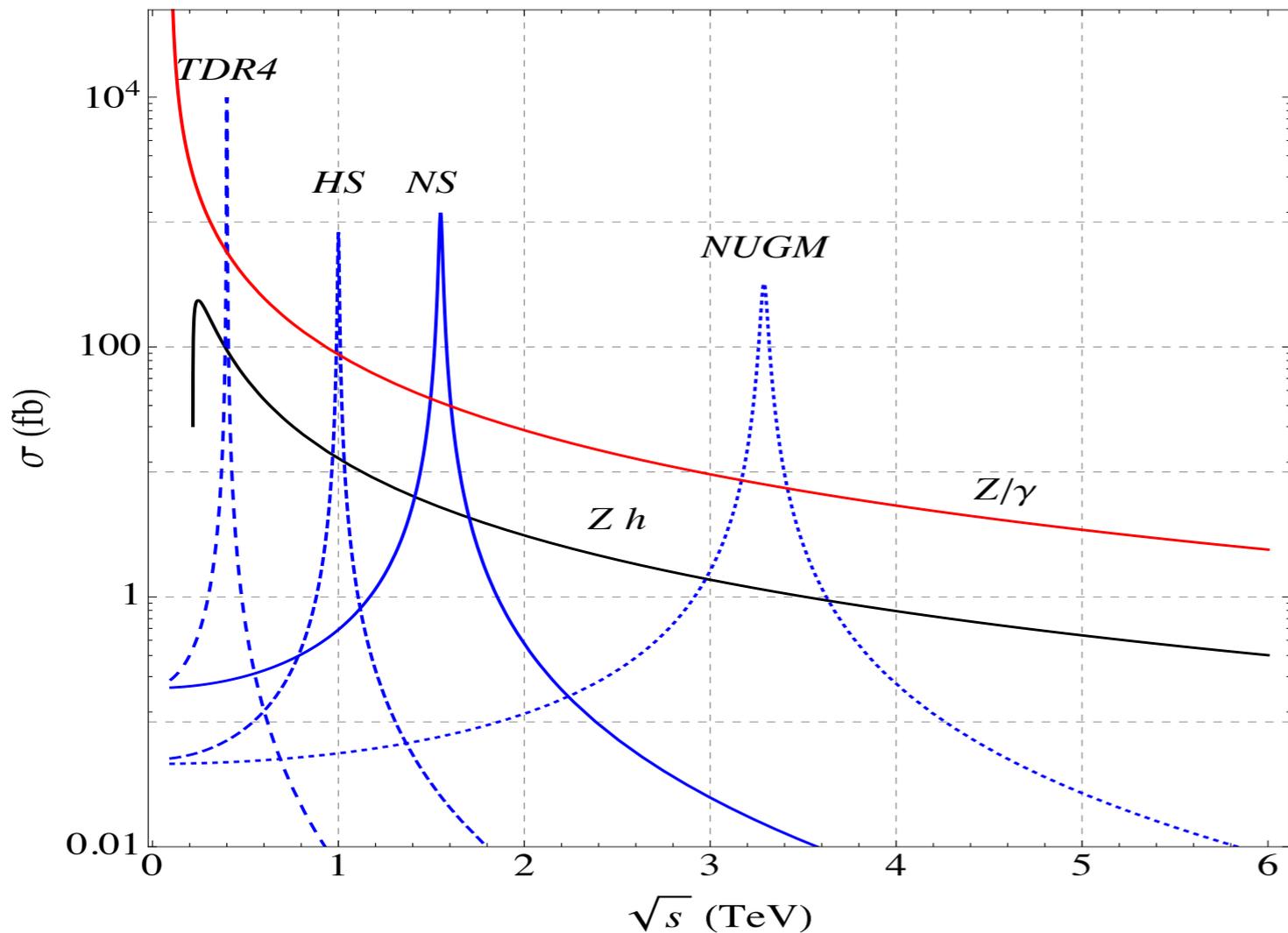
from Higgs (h) coupling measurements, we know H/A are essentially decoupled from WW/ZZ and are **narrow**

$m_H \sim m_A$  not pinpointed by naturalness, but also not tightly bounded at LHC

H/A can be produced as s-channel resonances at a  $\mu$ -collider.

Tuning  $\sqrt{s} \sim m_H$ , rate becomes enormous

$$\begin{aligned} \text{Events/year} &= 1.54 \times 10^5 \quad ( \\ &\times \left( \frac{\mathcal{L}}{10^{34} \text{ cm}^{-2} \text{ s}^{-1}} \right) \left( \frac{1 \text{ TeV}}{m_{H/A}} \right)^2 \left( \frac{BR(H/A \rightarrow \mu^+ \mu^-)}{10^{-4}} \right) \end{aligned}$$



depending on H/A separation, width, and energy resolution, two distinct peaks may be seen

if  $m_H > 2 m_X$  for some superpartner (electroweakinos!),  
 $pp \rightarrow H/A$   
 is a new SUSY source

even at ~few % BR,  $pp \rightarrow H/A \rightarrow XX$  can far exceed other X production modes

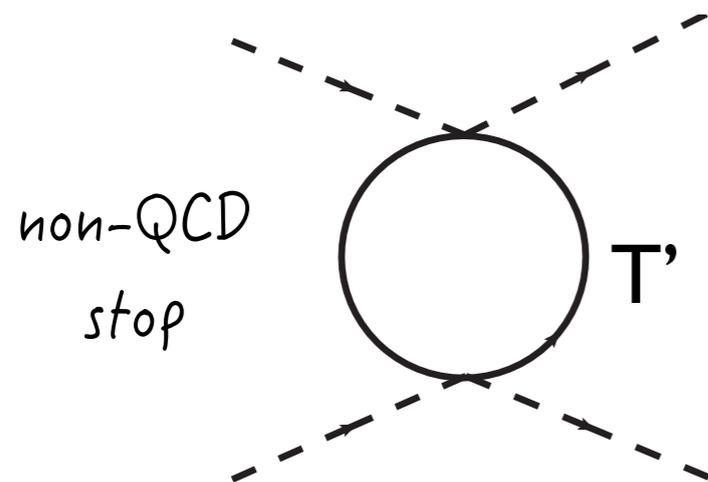
nasty scenarios still exist...

cancellation of quadratic sensitivity of Higgs mass does not require top-partner has QCD color, just the same # of d.o.f.

could have a SUSY where the stop is not colored under our QCD!

'Folded Supersymmetry' [Burdman, Chacko et al '06]

little studied, but best option is likely precision Higgs



→  $\#|DH|^2$ , so acts as a wave-function renormalization & shifts all Higgs couplings

[Craig, Englert, McCullough '13]

# Conclusions

direct LHC constraints and  $m_h = 126$  GeV have cut a swath out of SUSY parameter space

‘Natural’ spectra remain the least constrained and are a main goal for LHC14 + beyond ( $m_{\text{stop}}, m_{\text{inos}} < \text{few TeV}$ )

to thoroughly search for &, if found, measure SUSY, a **high-energy, high precision** lepton collider is the best tool

if  $\mu$ -collider is the best combination of these traits, its the machine to use (added bonus of s-channel H/A factory)

updated, detailed studies of  $\mu$ -collider capabilities for precision SUSY/DM studies motivated

EXTRAS

# more detailed limits

